Reciprocity with Virtual Nodes: Supporting Mobile Peers in Peer-to-Peer Content Distribution

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***Abstract*—The Peer-to-Peer (P2P) paradigm offers scalable means to perform bulk data distribution, e.g., for small businesses which cannot afford huge upfront investments, by incorporating user's resources in the dissemination process. Due to the proliferation of smartphones with wireless broadband connectivity and the increasing convergence of fixed and mobile platforms, a growing number of users are expected to participate in P2P content distribution networks wirelessly. However, the P2P approach only works if users are willing to contribute resources. A commonly applied incentive scheme is the well-known Tit-for-Tat approach, where each peer is forced to contribute as much bandwidth to the network as he consumes. Nevertheless, reciprocal schemes discriminate resource poor mobile devices in terms of energy and upload bandwidth, as they are device-bound instead of being user-bound. In this work, an incentive scheme featuring virtual nodes is presented, which allows mobile devices to seek help from other devices owned by its user, e.g., the user's home gateway or a supporting cloud instance. Preliminary results are presented in the scope of a P2P streaming scenario.**

I. Introduction

Peer-to-Peer (P2P) protocols are a scalable solution for the distribution of high data volumes to end-users. With the rapid adoption of smartphone hardware offering mobile broadband access, traditional file sharing protocols such as BitTorrent [2], [18] are currently starting to show up in mobile access studies and are expected to increase in share [13]. This expectation is motivated by the fast convergence of mobile and fixed computing, which comes with a convergence of use cases, as users are assumed to demand access to the same services and applications on all platforms. In fact, first implementations of P2P file sharing and streaming apps are hitting the marketplaces. However, the design of mobile P2P content distribution protocols has its own challenges.

Mobile peers have more limited capacities than stationary peers; especially energy efficiency is a crucial factor. As P2P protocols rely on the contribution of resources of clients, such protocols imply additional efforts from all participating devices. In the case of content distribution, contribution of resources is commonly enforced using a reciprocal incentive scheme, such as in BitTorrent [2], [16]. While reciprocity is doable for stationary peers, it heavily affects mobile peers, as the download of data can be performed with considerably lower power consumption than uploading data, because the latter requires the mobile device to provide the additional transmission power for reaching the remote access point or cell tower, as shown in Figure 1. Performing an upload and download at the same time versus performing a pure download consumes 101 mW / 122 mW more power on average (depending on the upload bitrate, Wi-Fi). For 3G link access technology, the difference is as high as 113 mW / 178 mW on average (depending on the upload bitrate, HSDPA)[1]. Thus, a protocol preventing mobile peers from uploading without sacrificing fairness can save energy in a magnitude of 34% (Wi-Fi) / 20% (HSDPA) of power consumption on the wireless interface. In fact, an even higher upload than download is a realistic setting for P2P streaming systems [12].

In the following, a reciprocal incentive scheme supporting virtual nodes is proposed. This allows mobile peers to seek help of trusted instances to perform the contribution of resources to the network, while the mobile peer is consuming only. The scheme can serve as a primitive for clustering trusted entities, e.g., by incorporating social data from Online Social Networks. First evaluation results applying the scheme to a P2P streaming use case are shown.

II. Related Work

Incentive schemes in P2P systems can be divided into reciprocal schemes, reputation-based schemes, and taxation-based schemes. The class of schemes explicitly addressing heterogeneous resources is the class is taxation-based schemes. These schemes apply contribution taxes according to a peer's available resources. The authors of [1] model peers as strategic agents, where the source sets a tax for each peer. In a follow-up paper, [4] try to fix shortcomings of [1] by distributing the announcement of taxes. The authors of [7] propose a taxation model for a Video on Demand streaming scenario, where taxes are set depending on the playback position of the peers. However, these schemes usually have the drawback of being applicable in trusted environments only [16], as there is no practical way to map an identifier (IP) to available resources in untrusted environments, i.e., the Internet.

To the best of the author's knowledge, there is only the work of [6] following the idea of virtual nodes in a reciprocal incentive scheme. The approach uses a centralized server for keeping contributions balanced, where the proposed approach is designed to work in a distributed way.

Also related to this approach is the concept of P2P proxies [5], which is compared to the presented solution in the scope of this work, showing that the idea of virtual nodes offers potential for considerable bandwidth savings.

[1] All measurements were conducted using a Nexus S smartphone, the confidence intervals are smaller than 1×10^{-3} Watt for $\alpha = 0.99$.

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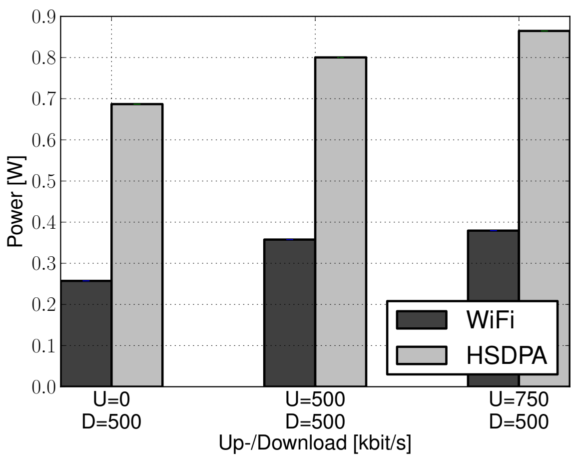


Fig. 1: Power consumption measurements of smartphone with different up-/download rates and link types. Confidence intervals ($\alpha = 0.99$) are printed, but smaller than 1×10^{-3} Watt.

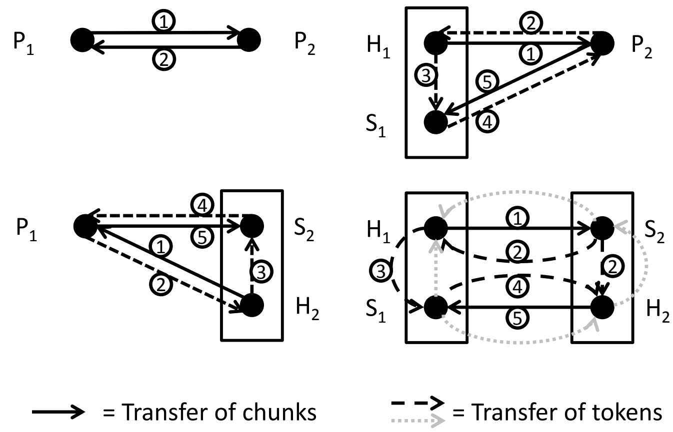


Fig. 2: The four cases of virtual node direct reciprocity. H denotes a helper instance, S denotes a sink, and P is a normal peer. Similar indices indicate membership of the same virtual node. Dashed lines represent the transmission of tokens.

III. Incentive Scheme

The incentive scheme's main task is to allow resource-poor devices to receive full quality of service in a P2P style system without sacrificing fairness. These requirements cannot be fulfilled with a standard incentive scheme based on direct reciprocity (Tit-for-Tat). However, direct reciprocity has a number desirable properties such as being prone to a number of attacks, comprising collusion of peers, whitewashing attacks (frequent rejoining to the system), sibyl attacks (joining with multiple identities), and byzantine attacks (varying behavior towards different peers). Moreover, direct reciprocity is efficient in isolating free riders, i.e., peers consuming resources from the network without contributing [16], [2], [18].

The incentive scheme proposed in this work is a generalization of a direct reciprocal scheme [2], allowing for the participation of peers with low resources while preserving the properties discussed above. For this purpose, *virtual nodes* are introduced. A virtual node consists of a *helper instance* and a number of *sinks*, where the helper instance is a user's home gateway or a supporting cloud instance, while the sinks represent mobile devices (see Figure 2). The central idea of this configuration is to handle the upload to the system in the helper instance, which uses a cheap, fixed access, whereas the mobile devices, using an expensive, cellular access only download from the network. However, the overall sum of contribution from and consumption of the virtual node should be kept in balance at any time.

As depicted in Figure 2, only one helper instance and one sink in a virtual node is considered in this work for the sake of brevity. Thus, there are four cases of reciprocal exchange to be handled, where two cases are symmetric.

1) $[P_1, P_2]$*:* A conventional peer P_1 bartering with a conventional peer P_2.

2) $[P_2, [S_1, H_1]]$ *and* $[P_1, [S_2, H_2]]$*:* In these cases, a conventional peer is bartering with a virtual node, i.e., P_1/P_2 downloads from a helper instance and uploads to a sink. As these cases are symmetric, $[P_1, [S_2, H_2]]$ are referred to as being representative for both cases from now on.

3) $[[S_1, H_1], [S_2, H_2]]$*:* In this case, a virtual node is bartering with a virtual node, where each helper instance is uploading to a sink in the other virtual node.

The simple case 1) can be handled easily by negotiating a chunk to trade and performing an exchange in a similar manner as BitTorrent's unchoking algorithm [2], [16]. Cases 2) and 3), however, are challenging, as they need efficient signaling mechanisms to prevent fraud. For this purpose, two additional concepts are introduced: a membership protocol/secure control channel is established within the virtual node and pull-tokens are introduced.

A pull token is a temporarily valid token that represents a debt of a peer towards a third party. Once a chunk has been uploaded to a peer, this peer can produce a token, which will grant a node possessing the token a chunk to download, or at least priority handling. The token exchange can be exemplified for case 2): H_1 uploads a chunk to P_2, which issues a token in exchange. When the token is received by H_1, it is immediately transmitted via the control channel to the sink S_1. S_1 redeems the token by transmitting the token to P_2 and receives a chunk in return. If P_2 is not cooperative, S_1 communicates this fact to H_1 via the control channel. H_1 reacts by stopping cooperation with P_2, thus creating an incentive for P_2 to always redeem valid tokens.

The scheme can also be used to barter between two virtual nodes (case 4). This requires two token streams, where each sink S_1/S_2 issues tokens, when it is served by one of the helper instances H_2/H_1. Note that in this case each sink also has to send a copy of issued tokens to its own helper instance in order to make the token known for redemption.

Tokens are not to be mistaken for a virtual currency. They are valid for a short time only and there is no way to accumulate them for later use. In fact, tokens are an identification mechanism to proof the eligibility to download a chunk. The simplicity of the mechanism has several advantages. As tokens are traded bilaterally only, there is no need to prevent the common problems of token based approaches like double spending [9], as a peer will simply not redeem a token twice. Thus, tokens can be implemented without using resource heavy cryptographic algorithms, e.g., a token can be represented by a random string of n bytes, where n is big enough to prevent guessing by attackers. Additionally, the token approach is very flexible: the helper instance can transfer its tokens to any node it deems appropriate. This way, even more than one sink can be supported by splitting the token stream to several sinks.

Fraudulent behavior regarding virtual node membership is prevented by a secure membership protocol among the members of a virtual node, using an extension of the Station-to-Station (STS) protocol by O'Higgins et al. [3]. Once authentication is performed, data transfer within the virtual node could be encrypted with a symmetric cryptographic algorithm to prevent the stealing of tokens. However, overhearing of tokens by an attacker is highly unlikely, as the attacker usually is not in the same collision domain as the user. Moreover, if an attacker can overhear tokens, he can also overhear transmitted video packets.

IV. Preliminary Results

In this section, a qualitative comparison to P2P proxy solutions is performed and the effectiveness of the chosen approach is shown using a numerical simulation model. The evaluation focuses on applying the scheme in a P2P streaming scenario.

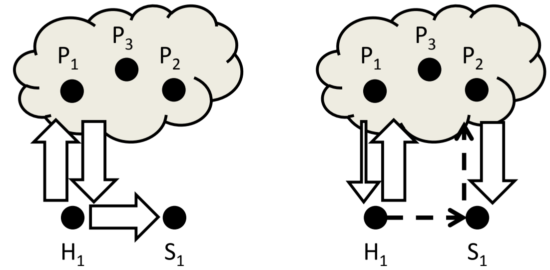
A. Comparison to Peer-to-Peer Proxy Concept

When compared to a P2P proxy solution, the proposed inventive scheme allows for the same effect: resource-poor clients are freed from the burden of contributing actively to the system. However, the proposed incentive scheme is shown to have considerable potential for optimization of overall traffic efficiency.

Figure 3 gives a simplified overview of the presumed traffic volumes generated by peers, helper instances and sinks in both cases, where 3a represents a P2P proxy solution and 3b represents the incentive scheme presented in this work.

In case of a P2P proxy solution, the helper instance H_1 (the proxy) has to download the complete stream of chunks from the network, indicated by the thick arrow from conventional peers to H_1. In turn, as a reciprocal incentive is applied, H_1 uploads the same amount of chunks to the network, where in the case of P2P streaming, the upload is usually even higher than the download. Additionally, H_1 is forwarding the stream to the sink S_1. Summing up, H_1 has to bring up at least twice the video bandwidth on the upstream and once the video bandwidth on the downstream.

In the proposed incentive scheme, in contrast, H_1's only purpose is the creation of credit among the bartering peers, which can be claimed and consumed by the sink S_1. More



(a) Data flow P2P proxy. (b) Data flow proposed incentive scheme.

Fig. 3: Data flow of P2P proxy versus data flow with proposed incentive scheme. Solid arrows indicate a transfer of chunks, dashed arrows depict token transmissions. The thickness of arrows indicates presumed traffic volumes.

importantly, this implies that H_1 is not dependent on downloading all chunks of the stream, which leaves opportunity for finding a bandwidth optimal piece picking strategy for H_1. This strategy can minimize H_1's download from the network, while spreading the incomplete set of downloaded chunks widely in the network, indicated by the combination of a small downstream arrow from the P2P network to H_1 and an upstream equivalent to the video bitrate. Besides that H_1 transfers tokens to S_1, which causes a negligible traffic volume compared to the size of the video stream.

B. Results from Network Simulation

The feasibility of the incentive scheme presented in this work is tested by implementing a numerical simulation model using the PeerFactSim.KOM [15] network simulation framework. Although P2P streaming is a widely researched topic, there is no standard/reference streaming overlay implementation to be used for experiments. Thus, this work is based on an overlay design incorporating state-of-the-art algorithms and mechanisms from literature.

The model is based on an unstructured topology (random mesh), as this type of topology has been shown to be more resilient to peer churn [17]. Video data is served in chunks, i.e., the video stream is broken down into pieces, which are treated as independent units by the network. A further crucial factor for the performance of streaming overlays are chunk scheduling strategies. A pull-based scheduling approach is++ implemented, i.e., peers request chunks actively, based on frequently exchanged buffer maps. Buffer maps indicate, which chunks a peer possesses and were shown to be an efficient signaling approach in the scope of streaming scenarios [14], [17].

The pool of simulated nodes is as large as 2500 conventional peers. An additional number of 200 virtual nodes (100 helper instances and 100 sinks) is deployed in the system. Of this overall number of 2700 nodes, at most 500 are online at the same time. The available bandwidth is drawn from a distribution based on an OECD broadband access study [10]. Session lengths and arrival patterns are based on a measurement study of the PPLive streaming system [8].

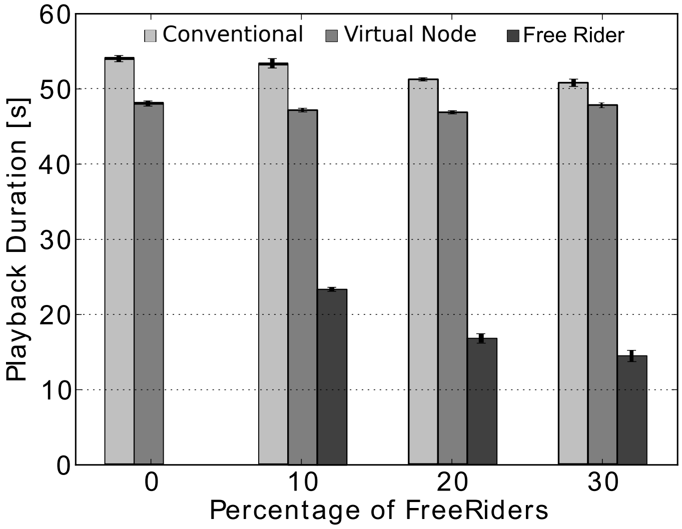


Fig. 4: Isolation of conventional peers, virtual nodes and free riders. Free riders get a considerable lower quality.

The overall applicability of the incentive scheme is tested by showing that the scheme can separate free riders efficiently by preserving a good playback quality for those nodes, who are contributing to the system, while punishing peers who do not. Figure 4 shows the average number of seconds per minute a peer can perform playback continuously under a varying fraction of free riders in the system. With an increasing amount of non-cooperative nodes in the system, the quality received by free riders even worsens, as the amount of free bandwidth given by cooperative peers is shrinking.

V. Conclusions and Outlook

The incentive scheme proposed in this work is a generalization of a reciprocal scheme, which is widely applied in the distributed systems domain. It allows setting up virtual nodes in the system to support resource poor peers without sacrificing fairness. Currently, the system is embedded in a video streaming scenario for the support of mobile peers, but is not limited to that.

The approach discussed in this work can be applied in other scenarios, where clusters of nodes trusting each other want to perform efficient load balancing. Besides optimizing and evaluating the system in the streaming scenario with respect to playback and bandwidth efficiency, it will be investigated how the system can be applied in this wider context. A possible extension is the clustering by using social data, where a peer can cluster with close nodes in the social graph to jointly share resources. The incorporation of multiple sinks can be reached easily, as the token based approach allows for spreading tokens to any number of trusted peers. Moreover, the incentive scheme can also be used to incorporate cloud instances in a P2P network, thus allowing a resource poor peer to pay for the generation of tokens to be consumed by his device.

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